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CURRENT AND FUTURE USAGE OF MATERIALS IN AIRCRAFT GAS TURBINE ENGINES

DEFENSE METALS INFORMATION CENTER
BATTELLE MEMORIAL INSTITUTE
COLUMBUS, OHIO 43201

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/s/ Dana Moran

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Director

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CURRENT AND FUTURE USAGE OF MATERIALS IN AIRCRAFT GAS TURBINE ENGINES

W. F. Simmons and H. J. Wagner*

BACKGROUND

The "Jet Age" in the United States is less than 30 years old. The first U. S. jet aircraft, the Bell P-59 Aerocomet, made its initial flight in October, 1942. Since that time, the gas-turbine-aircraft-engine industry has grown to vigorous maturity. A dramatic illustration of this growth is shown in Figure 1 by the size of the new McDonnell Douglas tri-jet, DC-10, compared with the DC-3. The 21-passenger DC-3, of 1936 vintage, is only slightly longer than the rear engine nacelle of the DC-10 Series 10. The new tri-jet is 179 ft. 8 in long, nearly 20 ft. in diameter, and the height to the top of the tail is 57 ft. 3 in.

Most of the aircraft gas-turbine engines currently produced in the United States are made by the following manufacturers:

AiResearch Manufacturing Division, The Garrett Corporation
Allison Division, General Motors Corporation
Continental Aviation and Engineering Corporation
General Electric Company
Lycoming Division, Avco Corporation
Pratt & Whitney Aircraft Division, United Aircraft Corporation

Some brief background information relating to the engine manufacturers is given in the following paragraphs. Additional manufacturer information is given in the Appendix which contains material applications in current aircraft gas-turbine engines and, as a matter of general interest, listings of engine designation, type, size, and the aircraft in which the engines are used.

AiResearch Manufacturing Division, The Garrett Corporation

AiResearch is the largest manufacturer of small gas-turbine engines. It makes the TPE 331 (military version T-76), a 500 to 840 hp turboprop engine used in a dozen commercial aircraft and in the North American-Rockwell OV-10A, Bronco. New facilities are being completed in Torrance, California, for the manufacture of a new high-bypass turbofan engine for corporate and commuter aircraft. Designated the ATF-3, it will be a 4000- to 5000-lb-thrust engine. Another new high-bypass engine, in the 2700- to 3000-lb-thrust class, is the TFE-731 to be built in Phoenix, Arizona. It is slated for certification in August, 1971, and will power the Swearingen SA-28T delta-wing business jet and an advanced model of the 10-place Learjet 25.

An experimental model of a hypersonic ramjet engine has been built by AiResearch for NASA Langley Research Center. This liquid-hydrogen-fueled engine is designed for speeds between Mach 3 and Mach 8. In this speed range, air inlet temperatures exceed 3600 F.

Allison Division, General Motors Corporation

Allison was the first U. S. company to mass produce turbojet engines, having won the production contract for the General Electric developed J33 and J35 engines. Over 90 percent of the jet engines produced in the U. S. up to 1950 were Allison products. In recent years, its most important products have been turboprop engines. The 501, producing about 4000 shaft horsepower (shp) and weighing about 1875 lb, is the powerplant for the Lockheed Electra and the Convair 580. The military version (T56) capable of producing about 4900 shp, is used for various military transports and Navy antisubmarine aircraft. Allison also produces a small turboshaft engine, the Model 250 (military version T63), producing 317 shp and weighing 139 lb. It is used on several commercial and military helicopters.

The new Allison turbofan engine, the TF41, is a joint Allison/Rolls-Royce development. It produces 14,250 lb thrust, weighs 3100 lb and is used on the Air Force LTV A-7D and the Navy LTV A-7E tactical fighter aircraft.

Continental Aviation and Engineering Corporation

Continental produces several turbojet engines in the range of 1025 to 2700 lb thrust. Most of these engines are for unmanned aircraft such as drones and missiles.

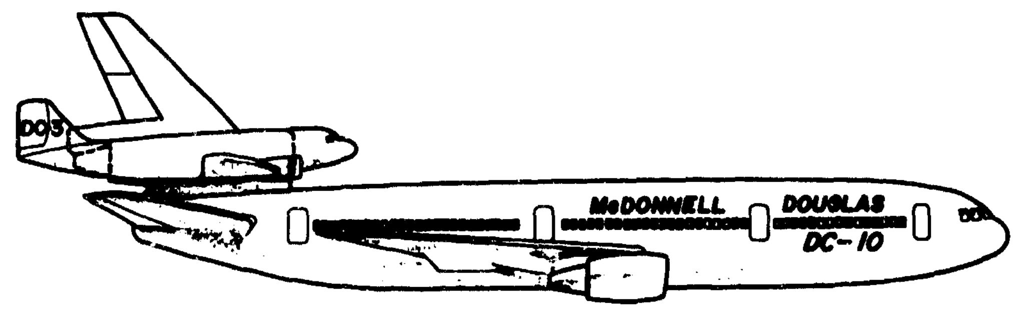

FIGURE 1. SIZE COMPARISON OF THE McDONNELL DOUGLAS DC-10 WITH THE DC-3.

* Advisor, Information Operations Division, and Chief, Specialty Alloys Division, respectively, Battelle Memorial Institute, Columbus, Ohio.

General Electric Company

The United States' first jet aircraft, the Bell P-59 Aerocomet, took to the air in October 1942 powered by twin General Electric 1-A jet engines. A total of 30 of these engines were produced. The first large-production General Electric engine was the J47. Between 1947 and 1956, 29,678 J47's were built by General Electric and another 6,154 by Packard and Studebaker. More recently the J79 has been the mainstay of General Electric's production: through the first quarter of 1969, they had produced 10,697 of them.

Currently, General Electric is building the GE4 (68,600 lb thrust) turbojet engine for the Boeing 2707-300, the TF39 (41,100 lb thrust) high-bypass turbofan engine for the Lockheed C-5A, and the CF6-6 (40,000 lb thrust) and the CF6-50 (47,300 lb thrust) for the McDonnell Douglas DC-10 Series 10 and Series 30 "Airbus". G. E. also produces a spectrum of smaller turbojet and turboshaft engines in their Lynn, Massachusetts plant: the J85, T58, T64 and the new TF30, a turbofan engine for the Navy Lockheed S3A airplane.

Lycoming Division, Avco Corporation

About 80 percent of all the helicopters in Vietnam are powered with Lycoming engines. These engines are small compared with the large jet engines used on conventional aircraft, producing between 1200 and 3750 shp and weighing between 540 and 800 lb. The Lycoming T53 and T55 engines have been in such short supply in Vietnam that engines needing overhaul are shipped by air to Corpus Christi, Texas for overhaul at the Army Aeronautical Depot Maintenance Center (ARADMAC) and then flown back to Vietnam. ARADMAC has been overhauling these engines at the rate of 500 per month.

Pratt & Whitney Aircraft Division, United Aircraft Corporation

Pratt & Whitney built their first 400 hp Wasp piston engine for aircraft in 1925, but it was not until after World War II that they entered the jet-engine field and started their rapid rise to their present position. The Pratt & Whitney J57 was the world's first twin-spool, axial-flow gas-turbine engine.

Today, most of the Boeing and McDonnell Douglas jet transports are equipped with Pratt & Whitney engines. The Boeing 747 and the McDonnell Douglas DC-10 Series 20 both will use the Pratt & Whitney JT9D turbofan engine which develops 45,500 lb thrust. The Pratt & Whitney TF30, an afterburning turbofan engine in the 20,000-lb-thrust class, powers the Air Force F-111 and the Navy F-14A. The TF30 is the world's first afterburning turbofan engine.

MATERIALS USAGE -- PAST, PRESENT, AND DEVELOPMENTAL

Compressors and Fans

Until recently, the operating conditions in the compressor section were such that titanium alloys, low-alloy steels, and stainless steels satisfactorily fulfilled all requirements. Table 1 lists the compositions of some of the current and future compressor-disk alloys and Table 2 lists compositions of some of the current and future compressor-blade and vane alloys.

Low-alloy and martensitic compressor-disk alloys such as "17-22A" and AISI 410 are disappearing in modern engines because higher compression ratios have raised compressor-disk temperatures above the limits for these materials. Superalloys, such as A-286, Incoloy 901, and Inconel 718 are required for disks as well as blades in the high-pressure compressors of advanced engines.

Incoloy 901 is regarded by Pratt & Whitney(1)* as a logical choice for service in a high-pressure compressor. It was originally developed for use in turbine disks operating in the 1200-to-1300 F temperature range. Since the turbine disks are creep-strength limited, the processing parameters were established to maximize the creep strength of disk forgings. However, service for compressor disks in the 800-to-1100 F temperature range is fatigue-strength rather than creep-strength limited. Therefore, it was necessary to modify the processing of Incoloy 901 disks to raise the fatigue strength for compressor applications. This was done at Pratt & Whitney by reducing the solution temperature from 2000 to 1800 F. The lower solution temperature resulted in an average grain size of ASTM 5-6, with no grain larger than ASTM 4. The 2000-F solution temperature had given an average grain size of 0 with some grains as large as 0.050-in. diameter. The finer and more uniform grain size resulted in a significant improvement in fatigue properties without significantly affecting the creep strength.

Advanced engines such as the GE4 will have a compressor inlet temperature of 500 F, a midpoint compressor temperature of about 800 F, and an exit temperature of 1000 to 1100 F. These operating conditions have led to the selection of Alloy 718, a nickel-base superalloy, for the last stages in the compressor.

It has been said that the advanced high-bypass engine could not be built without titanium alloys. This is true today, but in the near future composites will be used in the fan parts and at the cold end of the compressor. Glass-reinforced plastics (already in use in the TF39) and graphite or boron-reinforced aluminum and epoxy are expected to be among the first composites to see service in gas-turbine engines.

The TF39 develops 80 percent of its thrust in the 1-1/2-stage fan which is 93 in. in diameter. The fan and the compressor spool are made of Ti-6Al-4V. The fan stator and casing are Ti-5Al-2.5Sn. For the spacers between the fan-stator vanes, glass-reinforced plastic stiffened with aluminum honeycomb has already replaced metal fabrications, yielding both a weight and cost advantage.

There are many low-stress low-temperature parts in the front end of subsonic engines that can be made of composite materials to save both weight and dollars. Some of these parts are being made

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* References are listed on page 14.

TABLE 1. COMPOSITION OF COMPRESSOR-DISK ALLOYS

Alloy	Nominal Composition, percent									
	C	Cr	Ni	Mo	Ti	Al	B	V	Fe	Other
2618-T6	- -	0.25Si[a]	1.0	- -	0.07	Bal.	1.3Cu	1.5 Mg	1.1	Each 0.05[a];total 0.15[a]
AISI 4340	0.40	0.8	1.8	0.25	- -	- -	- -	- -	Bal.	
"17-22A"	0.45	1.25	- -	0.50	- -	- -	- -	0.25	Bal.	
"17-22A"S	0.30	1.25	- -	0.50	- -	- -	- -	0.25	Bal.	
B5F5	0.45	1.00	- -	0.55	- -	- -	- -	0.30	Bal.	
AISI 410	0.15[a]	12.5	- -	- -	- -	- -	- -	- -	Bal.	
Greek Ascoloy	0.12	13.0	2.0	- -	- -	- -	- -	- -	Bal.	3.0W
17-4PH	0.06	16.0	4.0	- -	- -	- -	- -	- -	Bal.	3.0Cu
AM-350	0.10	16.5	4.25	2.75	- -	- -	- -	- -	Bal.	
AM-355	0.15	15.5	4.25	2.75	- -	- -	- -	- -	Bal.	0.10N
A-286[b]	0.05	15.0	26.0	1.25	2.15	0.2	0.003	0.30	Bal.	
Incoloy 901	0.05	13.5	42.7	6.2	2.5	0.25	- -	- -	34.0	0.10Cu
Inconel 718[b]	0.05	19.0	53.0	3.0	0.8	0.6	0.004	- -	19.0	5.2Cb
Waspaloy	0.07	19.5	Bal.	4.3	3.0	1.4	0.006	- -	- -	0.09Zr, 13.5Co
Ti-6Al-4V	- -	- -	- -	- -	Bal.	6.0	- -	4.0	- -	
Ti-6Al-2Sn-4Zr-2Mo[b]	- -	- -	- -	2.0	Bal.	6.0	- -	- -	- -	4Zr, 2Sn
Ti-6Al-6V-2Sn[b]	- -	- -	- -	- -	Bal.	6.0	- -	6.0	- -	2Sn
Ti-8Al-1Mo-1V	- -	- -	- -	1.0	Bal.	8.0	- -	1.0	- -	
IMI-679 (British)	0.04	- -	- -	1.0	Bal.	2.2	- -	- -	- -	5Zr, 11Sn

(a) Maximum

(b) Under consideration for application in advanced engines

TABLE 2. COMPOSITIONS OF COMPRESSOR-BLADE AND VANE ALLOYS

Alloy	Nominal Composition, percent									
	C	Cr	Ni	Mo	Ti	Al	B	V	Fe	Other
AISI 410	0.15[a]	12.5	- -	- -	- -	- -	- -	- -	Bal.	
17-4 PH	0.06	16.0	4.0	- -	- -	- -	- -	- -	Bal.	3.0Cu
Greek Ascoloy	0.12	13.0	2.0	- -	- -	- -	- -	- -	Bal.	3.0W
Jethete 152 (British)	0.10	12.0	2.5	1.75	- -	- -	- -	0.33	Bal.	
A-286	0.05	15.0	26.0	1.25	2.15	0.2	0.003	0.30	Bal.	
Inconel X-750	0.04	15.0	73.0	- -	2.5	0.8			6.75	0.85Cb
Inconel 718	0.05	19.0	53.0	3.0	0.8	0.6	0.004	- -	19.0	5.2Cb
Ti-6Al-4V	- -	- -	- -	- -	Bal.	6.0	- -	4.0	- -	
Ti-8Al-1Mo-1V	- -	- -	- -	1.0	Bal.	8.0	- -	1.0	- -	
Ti-6Al-2Sn-4Zr-2Mo[b]	- -	- -	- -	2.0	Bal.	6.0	- -	- -	- -	4Zr, 2Sn
Ti-6Al-6V-2Sn[b]	- -	- -	- -	- -	Bal.	6.0	- -	6.0	- -	2Sn
IMI 679 (British)	0.04	- -	- -	1.0	Bal.	2.2	- -	- -	- -	5Zr, 11Sn

(a) Maximum

(b) Under consideration for application in advanced engines

using today's materials and processing technology. The next generation of engines will contain a significant increase in the use of composite parts. However, composite materials have not yet been proven ready to meet commercial-airline reliability requirements as far as erosion resistance and foreign-object damage (FOD) are concerned, and are therefore not yet used in rotating components of U. S. built engines.

Hollow construction of titanium-alloy fan and compressor blades may permit substantial weight reductions without sacrificing resistance to erosion and FOD, and is being considered for blades in advanced engines.

A reduction in engine sound level is desirable, and engine manufacturers are working on this problem. Steps being taken are based on these ideas:

(1) A high-bypass ratio can cut the exhaust velocity in half and thus reduce the jet noise.

(2) Elimination of inlet guide vanes helps reduce noise.

(3) Low fan tip speeds help reduce noise.

(4) A wider clearance between the fan and subsequent compressor stages reduces the sound level. Both Boeing and McDonnell Douglas, under NASA contracts, are investigating nacelle modifications that would reduce fan-compressor noise. They appear to have been successful, but the cost to modify existing aircraft will be high. (See Aviation Week and Space Technology, Oct. 27, 1969, page 31.) The McDonnell Douglas modification includes a lengthened fan discharge duct and a single-ring inlet. Both sides of the concentric inlet ring were treated with sound absorbing honeycomb sandwich material.

(5) Plastic sound-absorbing material for fan duct surfaces and the fan frame flow path might cut the sound level.

Aviation Week, June 16, 1969, has this comment regarding the General Electric CF6 engine for the McDonnell Douglas DC-10, "General Electric has developed a glass-fiber sandwich structure which has emerged as the favored sound attenuation material. It is a 1-inch thick sandwich consisting of a perforated glass-fiber face sheet, a double-diamond truss core, and a solid glass-fiber face sheet, which acts as a backstop for the sound energy. This material will be installed from the inlet lip downstream to the trailing edge of the outer fan air duct wall."

Developmental Titanium Usage

The large high-bypass turbofan engines could not have been developed without strong lightweight titanium alloys. The percentage of titanium alloy in the TF39 engine for the C5A has reached 32 percent of the total metals weight in the engine. This may be the high point for titanium usage in jet engines, because two factors will work to reduce the application of titanium. The first is the use of composites, which is just beginning. Large fan parts that now account for most of the titanium alloy usage can probably be made largely of composites. The second factor is the increased temperature in the compressors of supersonic engines, which has already necessitated the replacement of several titanium stages in the hot end by parts made of a nickel-base alloy. However, new manufacturing techniques may result in lighter hollow titanium fan and compressor blades which could make it quite difficult for composites to replace titanium.

Ti-6Al-4V alloy has been the high-volume alloy in gas-turbine engine applications, with some Ti-8Al-1Mo-1V and Ti-5Al-2.5Sn alloys being used. It is expected that Ti-6Al-2Sn-4Zr-2Mo and Ti-6Al-6V-2Sn alloys will reach high-volume usage in advanced engines. Table 3 lists the titanium parts in a typical modern fan-jet engine along with alternate titanium alloys and competing materials for the parts.

Figure 2 shows the relationship between the design stress/density ratio and temperature for composites, titanium alloys, and superalloys. This figure shows how the titanium range is being compressed to between about 400 and 800 F by the composites and the superalloys.[2]

On the other hand, new titanium alloys are being developed and, if most of the manufacturing and application problems can be solved, titanium will continue to hold its own in jet-engine usage. The total mill products for aircraft engines is expected to increase as shown in Figure 3. Some of the problems and handicaps that are unique to (or accentuated in) titanium have been listed by L. P. Jahnke, of General Electric Company as follows:[2]

Problems in manufacturing:

(1) Segregation
(2) Production of large precision forgings
(3) Production of precision castings
(4) Material cost.

Problems in applications:

(1) Erosion
(2) Foreign object damage
(3) Fretting
(4) Surface sensitivity
(5) Salt stress corrosion
(6) Oxidation embrittlement
(7) Structural stability
(8) Fire.

Table 4, prepared for DMIC by R. A. Wood in April, 1969, shows the estimated fly weight of titanium in aircraft engines.

Combustors

The alloys used for combustors and their liners and for the transition ducts connecting the combustors to the turbine inlet nozzles, must be formable, weldable sheet alloys capable of 8000 to 10,000 hours of operation in an oxidizing environment at average metal temperatures of about 1650 F or more. These sheet alloys must be stable for this long-time high-temperature service and have optimum

TABLE 3. TITANIUM PARTS IN A "TYPICAL" MODERN FAN-JET ENGINE

Part	Material	Alternate Ti Alloy[a]	Alternate Material[a]
Inlet case	5Al-2.5Sn	Ti,[b] 8Al-1Mo-1V	12Cr 'stainless' steel
Fan blades	8Al-1Mo-1V	6Al-4V, 6Al-6V-2Sn	Composites[c]
Fan disks	8Al-1Mo-1V	6Al-4V, 6Al-6V-2Sn, Ti 679	Low-alloy steel, 12Cr steel
Fan exit struts	6Al-4V	Ti,[b] 5Al-2.5Sn	12Cr steel
Fan duct	Ti, 5Al-2.5Sn	8Al-1Mo-1V	Al alloy
Fan duct fairings	Ti[b]	5Al-2.5Sn	Al alloy
Front compr. blades	8Al-1Mo-1V	6Al-4V, 6Al-6V-2Sn	12Cr steel
Front compr. disks	8Al-1Mo-1V	6Al-4V, 6Al-6V-2Sn	Low-alloy steel, 12Cr steel
Front compr. case	6Al-4V	5Al-2.5Sn, 6Al-1Mo-1V	12Cr steel
Intermediate case	5Al-2.5Sn	8Al-1Mo-1V	12Cr steel
Rear compr. blades	8Al-1Mo-1V	6Al-4V, 6Al-2Mo-4Zr-2Sn, Ti 679	12Cr steel, Ni alloy

Titanium Alloy Utilization for "Typical" Engine

Alloy	Form	Finished Part Weight, lb	Raw Material Weight, lb	Utilization, % (Finished/Raw Wgt.)
Ti	Sheet	142.2	210.0	67.7
	Bar and forging	27.8	299.4	9.3
5Al-2.5Sn	Sheet	121.2	256.8	47.2
	Bar	5.3	64.7	8.2
	Forging	183.6	2366.4	7.8
6Al-4V	Bar and forging	223.8	1544.0	14.5
8Al-1Mo-1V	Bar	2.0	15.3	13.1
	Forging	238.0	1152.8	20.6
Total Titanium Alloy		944.3	5909.4	16.0

(a) Depending on temperature, stress, corrosive resistance, cost, and weight requirements.

(b) Commercially pure titanium A-55 or A-70 grade.

(c) Such as graphite fiber-reinforced epoxy, boron-reinforced aluminum, etc.

erosion-corrosion, thermal fatigue (cracking), and distortion resistance. Most manufacturers now use annular combustors, which give a more even temperature distribution at the turbine nozzle. Liners are always air-film cooled and are often coated for additional protection. Coatings improve the resistance to erosion-corrosion damage and may assist in distributing the heat flux more evenly.

Currently Hastelloy X is by far the most commonly used alloy for combustor liner applications. L-605 and N-155 alloys have also been used, and AISI Type 321 and 310 alloys may be used at lower temperatures, as in stationary gas turbines. Haynes Developmental Alloy No. 188, which is superior to Hastelloy X in high-temperature strength, ductility, and oxidation resistance, is receiving much attention from engine builders for combustor applications. Table 5 lists some typical combustor alloys.

In the future, coated TD-Nickel or TD-NiCr may be used in combustor applications. Thoria dispersions in nickel produce a material that is stronger than conventional superalloys in the 1800 to 2300 F temperature range. These dispersion strengthened materials also are superior in thermal fatigue and thermal distortion resistance. A drawback to the use of TD-Ni is its poorer oxidation-corrosion-erosion resistance, requiring that protective coatings be used. TD-NiCr has better surface properties,

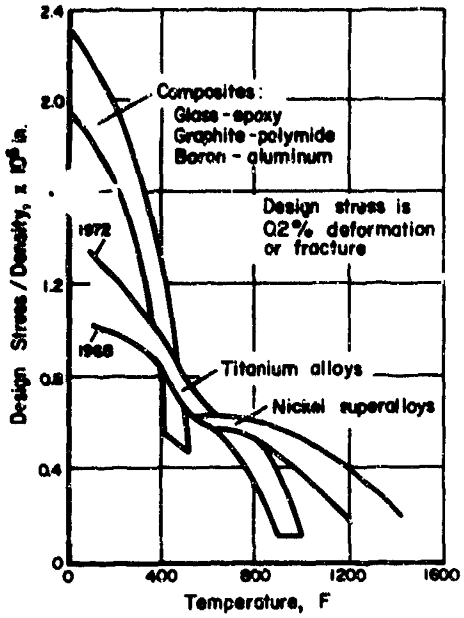

FIGURE 2. TITANIUM VERSUS COMPOSITES AND SUPERALLOYS (General Electric Company, Reference 2)

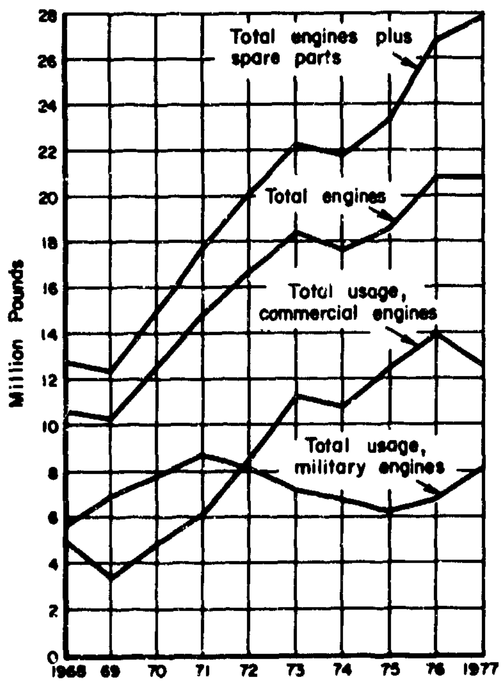

FIGURE 3. TITANIUM MILL PRODUCTS FOR AIRCRAFT ENGINES 1968-1977 (MAB Report 249, February 1969)

TABLE 4. AIRCRAFT SYSTEMS HAVING TITANIUM-ALLOY CONTENT

Airframe	Engine	Ti, Fly Weight in Engine, lb (estimated)
Douglas A-4E/F	(E) PW-J52-P-6	300
	(F) PW-J52-P-8A	300+
Grumman A-6A/B	PW-J52-P-8A	300+
McDonnell F-4 Series	GE-J79-8	125
RF-4C/D/E	GE-J79-15	100
F-4J	GE-J79-10	Not available
F-4K/M	Rolls-Royce models	Not available
Northrop F-5A	GE-J85-13	Not available
LTV A-7A (Navy)	PW-TF30-P-6	850
A-7D (USAF)	Allison/RR TF41-A-1	Not available
A-7E (Navy)	Allison/RR TF41-A-1	Not available
G. Dynamics		
F-111A	PW-TF30-P-3	850
F-111B	PW-TF30-P-3/8	850
Lockheed YF-12A	PW-J58	800
SR-71	PW-JT11D-20B	
C-141A	PW-TF33-P-7	637
C5A	GE-TF-39	2100
NAR OV-10A	AiResearch T-76	25
Sikorsky CH-53 type	GE-T64-6	Not available
Lockheed AAFSS	GE-T64-16	Not available
Boeing 707-320	PW-JT4A-11	385
707-320B	PW-JT3D-3B	565
707-720 (EB,C)	PW-JT3C/D-12/3	586
727-200	PW-JT8D-1/7	351
737-100	PW-JT8D-1/7	351
747-136	PW-JT9D	2300
2707 (SST)	GE-GE4	1000
Douglas DC-8 Series	PW-JT3D-3/3B	565
DC-9 Series	PW-JT8D-1 or 5 or 7	351
DC-10-10	GE-CF6-6	Not available
DC-10-20	PW-JT9D	2300
DC-10-30	GE-CF6-50	Not available
Lockheed 107C (or L-500)	GE-CTV-39	1200
L-1011 (Tristar)	RB-211	Not available
- -	Lycoming T53-L-5	25

TABLE 5. COMPOSITIONS OF COMBUSTOR ALLOYS

Alloy	Nominal Composition, percent							
	C	Cr	Ni	Co	Mo	W	Fe	Other
AISI 310	0.05	25.0	20.0	- -	- -	- -	Bal.	
AISI 321	0.05	18.0	10.5	- -	- -	- -	Bal.	0.42Ti
AISI 347	0.05	18.0	10.5	- -	- -	- -	Bal.	0.50Cb
Inconel 600	0.04	15.8	Bal.	- -	- -	- -	7.2	
Inconel 625[a]	0.05	22.0	Bal.	- -	9.0	- -	3.0	3.6Cb
N-155, Multimet	0.15	21.0	20.0	20.0	3.0	2.5	Bal.	1.0Cb,0.15N
Hastelloy X	0.10	22.0	Bal.	1.5	9.0	0.6	18.5	
Haynes Alloy 188[a]	0.08	22.0	22.0	Bal.	-	14.0	1.5	0.08La
C263(British)	0.06	20.0	Bal.	20.0	5.9			2.2Ti,0.5Al
L-605,WF-11, HS-25	0.10	20.0	10.0	Bal.	- -	15.0	-	
TD-Nickel[a]	- -	- -	Bal.	- -	- -	- -	- -	2.0ThO_2
TD-NiCr[a]	- -	20.0	Bal.	- -	- -	- -	- -	2.0ThO_2

(a) Under consideration for application in advanced engines

and may be used at 2200 F without coating, however, it is still an experimental material and has not been produced in commercial quantities. Both dispersion strengthened materials are difficult to fusion-weld without gross loss in strength because of agglomeration of the dispersoids. Because of this agglomeration problem, processes such as resistance spot and seam welding, diffusion bonding, and mechanical joining are used.

Smoke reduction of jet engines has been receiving considerable attention from engine builders. However, this is more a design problem than a material problem. Component tests of combustors having advanced dome and nozzle design have given virtually smoke-free operation.

Turbines

The turbine section of the gas turbine engine is probably more demanding of the materials engineer than any other part of the engine. Here the highest temperatures and stresses are encountered. Turbine inlet temperatures (gas temperature) in advanced engines will approach 3000 F within the next decade. The use of increasingly more cooling is the only alternative to the use of refractory metals or ceramics.

Disks

Materials for turbine disks in the past have been low-alloy steels and iron-base alloys such as 16-25-6, A-286, V-57, and Incoloy 901. The disks in production engines are alloys such as A-286, Incoloy 901, D-979, and Waspaloy. The trend to higher operating temperatures will require the use of superior alloys. Among the disk alloys selected for advanced engines are Waspaloy, Alloy 718, René 95, and Astroloy.

For some of the smaller engines such as the Allison 250 and the AiResearch 331 and T76, the wheels (disks) are precision cast integrally with the blades. For this purpose, alloys such as Alloy 713LC (coated), IN 100, and MAR-M-211 have been used.

Research is underway to improve the casting techniques so that larger wheels and blades can be integrally cast from the stronger nickel- and cobalt-base casting alloys.

Some typical turbine disk alloys are listed in Table 6.

Blades

In the past, turbine blades have been made from iron-, nickel-, or cobalt-base alloys, both cast and forged. Currently, however, practically all of the turbine blades are made from either cast or forged nickel-base alloys, and the trend is toward increased use of castings. There are several reasons for this trend:

(1) Through variation in composition, casting alloys can be made that are inherently stronger than the workable alloys.

(2) At high temperatures, cast alloys are usually stronger than wrought alloys of the same composition.

(3) The relative ease with which complex air-cooled precision cast blades and vanes can now be made is an advantage in engine design. This advance in the state of the art of casting is largely due to the development of high quality core materials and improved temperature and solidification control

(4) Complex precision castings are now reliably producible.

(5) The economics now favor castings for complex parts such as air-cooled blades and vanes.

(6) Cast blades are less susceptible to thermal fatigue cracking than are forged blades.

(7) Special structures, such as directionally solidified grains, can be obtained.

Turbine blades are subjected to a severe combination of high temperature and high stress. Current materials have sufficient creep-rupture resistance to minimize failure by creep for extended time periods at rated speeds and temperatures. Blades are inspected and measured during engine overhaul and those that have increased in length or changed shape because of creep are replaced. Thermal fatigue cracking appears to be the predominant blade failure process today. Engine starts and stops and even the heating and cooling during engine acceleration and deceleration contribute to the nonuniform stresses that cause thermal fatigue cracking of the leading or trailing edges.

Hot corrosion (sulfidation) has been a problem for some military and commercial aircraft operating in marine atmospheres. Particularly susceptible are low-chromium (less than 12 percent) nickel-base alloy blades operating at higher than average metal temperatures. Protective coatings have given relief, and the trend now appears to be toward the use of coatings wherever they can increase the service life, whether the problem is sulfidation, corrosion, oxidation or erosion.

Table 7 shows some representative turbine-blade alloys.

Vanes

The first-stage nozzle vanes are the hottest part in the engine and are subject to tremendous thermal shock stresses. They take the first impact of the hot gas from the combustors as they direct it into the turbine inlet. These vanes are usually coated for improved oxidation resistance and may be air cooled. Since they are stationary they are not highly stressed. Cast nickel- and cobalt-base alloys are usually used for the first- and second-stage vanes. Hollow blades are less subject to thermal stresses that result in thermal fatigue and both sheet metal and cast hollow blades are used. As an example of hollow sheet-metal vanes, the GE J79 engine has stator vanes in the first two stages that are fabricated from René 41 alloy and third-stage vanes that are fabricated from A-286. Both of these alloys are relatively easy to form and weld, with proper precautions.

TABLE 6. TURBINE DISK ALLOYS

Alloy	Nominal Composition, percent												
	C	Cr	Ni	Co	Mo	W	Cb	Ti	Al	B	Zr	Fe	Other
"17-22A"S	0.30	1.25	- -	- -	0.50	- -	- -	- -	- -	- -	- -	Bal.	0.25V
H-53V (British)	0.08	10.6	0.55	6.5	0.80	- -	0.40	- -	- -	- -	- -	Bal.	
Greek Ascoloy	0.12	13.0	2.0	- -	- -	3.0	- -	- -	- -	- -	- -	Bal.	
Timken 16-25-6	0.08(a)	16.0	25.0	- -	6.0	- -	- -	- -	- -	- -	- -	Bal.	0.15N
A-286	0.05	15.0	26.0	- -	1.25	- -	- -	2.15	0.2	0.003	- -	Bal.	0.3V
Discaloy	0.04	13.5	26.0	- -	2.75	- -	- -	1.75	0.1	- -	- -	Bal.	
CG 27	0.05	13.0	38.0	- -	5.5	- -	0.60	2.5	1.5	0.01	- -	Bal.	
V-57	0.08(a)	15.0	27.0	- -	1.25	- -	- -	3.0	0.25	0.01	- -	Bal.	0.5V(a)
Incoloy 901	0.05	13.5	42.7	- -	6.2	- -	- -	2.5	0.25	- -	- -	Bal.	
Inconel 718(b)	0.04	19.0	52.5	- -	3.0	- -	5.2	0.8	0.6	- -	- -	Bal.	
Waspaloy	0.07	19.5	Bal.	13.5	4.3	- -	- -	3.0	1.4	0.006	0.09	- -	
D-979	0.05	15.0	Bal.	- -	4.0	4.0	- -	3.0	1.0	0.01	- -	27	
René 41	0.09	19.0	Bal.	11.0	10.0	- -	- -	3.1	1.5	0.01	- -	- -	
Astroloy	0.06	15.0	Bal.	15.0	5.25	- -	- -	3.5	4.4	0.03	- -	- -	
René 95(b)	0.15	14.0	Bal.	8.0	3.5	3.5	3.5	2.5	3.5	0.01	0.05	- -	

(a) Maximum

(b) Under consideration for application in advanced engines.

TABLE 7. TURBINE-BLADE ALLOYS

Alloy	Nominal Composition, percent											
	C	Cr	Ni	Co	Mo	W	Cb	Ti	Al	B	Zr	Other
Inconel X-750	0.04	15.0	73.0	- -	- -	- -	0.85	2.5	0.8	- -		6.75Fe
M-252	0.15	19.0	Bal.	10.0	10.0	- -	- -	2.5	1.0	0.005	- -	
Waspaloy	0.07	19.5	Bal.	13.5	4.3	- -	- -	3.0	1.4	0.006	0.09	
René 41	0.09	19.0	Bal.	11.0	10.0	- -	- -	3.1	1.5	0.008	- -	
Inconel 700	0.12	15.0	46.0	28.5	3.75	- -	- -	2.2	3.0	- -	- -	
Udimet 500	0.08	19.0	Bal.	19.5	4.0	- -	- -	2.9	2.9	0.01	- -	
GMR-235 D(a)	0.15	15.5	Bal.	- -	5.0	- -	- -	2.5	3.5	0.05	- -	
Udimet 700	0.10	15.0	Bal.	18.5	5.2	- -	- -	3.5	4.25	0.02	- -	
Alloy 713C(a)	0.12	12.5	Bal.	- -	4.2	- -	2.0	0.8	6.1	0.012	0.10	
Alloy 713LC(a)	0.05	12.0	Bal.	- -	4.5	- -	2.0	0.6	5.9	0.01	0.10	
MAR-M 200(a)	0.15	9.0	Bal.	10.0	- -	12.5	1.0	2.0	5.0	0.015	0.05	
MAR-M 211(a)	0.15	9.0	Bal.	10.0	2.5	5.5	2.75	2.0	5.0	0.015	0.05	
Nimonic 80A(c)	0.10	19.5	Bal.	- -	- -	- -	- -	2.3	1.35	.030	0.5Fe	
Nimonic 105(c)	0.15	14.9	Bal.	20.0	5.0	- -	- -	1.50	5.25	0.03		
Nimonic 108(c)	0.14	14.9	Bal.	20.0	5.25	- -	- -	1.25	5.0	0.03		
Nimonic 118(c)	0.14	15.0	Bal.	15.0	4.0	-	- -	4.0	5.0	0.03		
IN-100	0.15	10.0	Bal.	15.0	3.0	- -	- -	4.75	5.5	0.015	0.05	1.0V
B-1900	0.10	8.0	Bal.	10.0	6.0	- -	- -	1.0	6.0	0.015	0.08	4.3Ta
X-40, HS 31	0.50	25.0	10.0	Bal.	- -	7.5	- -	- -	- -	- -	- -	
René 80(b)	0.17	14.0	Bal.	9.5	4.0	4.0	- -	5.0	3.0	0.015	0.03	
MAR-M-421(a)(b)	0.15	15.5	Bal.	10.0	1.75	3.0	1.75	1.75	4.25	0.015	0.05	

(a) Cast alloys.
(b) Under consideration for application in advanced engines.
(c) British

Table 8 lists the best known cast nickel- and cobalt-base vane alloys.

Developmental Superalloys

Research programs are being conducted by both industry and government for the purpose of developing alloys with improved hot strength, better microstructural stability after long-time exposure at elevated temperature, and improved resistance to attack by combustion products containing sulfur and sea salt (hot corrosion/sulfidation). Some of the new experimental superalloys are given in Table 9.

Refractory Metals

During the past decade there has been extensive government-supported research on the refractory metals -- columbium, tantalum, molybdenum, and tungsten. At present, columbium base alloys containing additions of tungsten, tantalum, and/or hafnium appear to be of potential importance in the design of future gas-turbine engines. However, all of the refractory alloys, because of their lack of oxidation resistance, must be coated, and to date a coating has not been found that would be fail-proof in creep, thermal fatigue, erosion, oxidation, and corrosion, except for very short times. The engine builders are in agreement that they will not use materials that are dependent upon coatings for their service life, although they will use coatings to extend an already acceptable service life. Specialists in the field of refractory metals are of the opinion that a revolutionary break-through in coating technology will be required before there is any significant use of refractory-metal alloys in gas-turbine engines.

Static Structures and Miscellaneous Components

Alloys that engine manufacturers have identified as being used for casings, shafts, and sheet components applications are listed in Tables 10, 11, and 12.

OTHER FUTURE MATERIALS AND PROCESSES TRENDS

The aircraft-engine industry has been the leader in the development of new materials and processes promoting increased efficiency and thrust-to-weight ratios in gas turbine engines. Since increased engine efficiency and operating temperature go hand in hand, the turbine inlet temperature of aircraft engines has been increased from about 1300 F in 1942 to the current level of 2300 F, or over. Figure 4 illustrates the effect of increased turbine inlet temperature on the performance of a typical turboshaft engine sized for about 4 lb/sec airflow and 8.0:1 compression ratio using either a regenerative or a nonregenerative engine cycle. For either cycle, increasing the turbine inlet temperature produces a substantial increase in specific horsepower and a modest decrease in specific fuel consumption. Experimental engines have been operated at temperatures up to about 3000 F. The increase in operating temperature already attained has depended primarily upon the development of advanced techniques for air cooling of vanes, blades, and associated engine parts made possible by refinements in casting and machining of the intricate cooling passages needed. At the same time, the use of new higher temperature nickel- and cobalt-base alloys in the turbine sections of the engine, and the use of titanium alloys, and, in advanced engines, composites and superalloys, in the compressor and fan sections, have contributed significantly to the advance in engine performance. Four cooling methods for blades and vanes have been classified as follows:

(1) Convection Cooling
(2) Impingement Cooling
(3) Film Cooling
(4) Transpiration Cooling.

The first three methods, shown schematically in Figure 5, are currently being used. Transpiration cooling is still experimental, but it shows enough promise so that manufacturers are looking for

TABLE 8. CAST COBALT-BASE AND NICKEL-BASE ALLOYS FOR NOZZLE VANES

Alloy	Nominal Composition, percent												
	C	Cr	Ni	Co	Mo	W	Cb	Ti	Al	B	Zr	Ta	Other
HS-21	0.25	27.0	2.5	Bal.	5.5	- -	- -	- -	- -	- -	- -	- -	
X-40, HS-31	0.50	25.0	10.0	Bal.	- -	7.5	- -	- -	- -	- -	- -	- -	
WI-52	0.45	21.0	1.0	Bal.	- -	11.0	2.0	- -	- -	- -	- -	- -	
MAR-M 302	0.85	21.5	- -	Bal.	- -	10.0	- -	- -	- -	0.005	0.20	9.0	
MAR-M 322	1.0	21.5	- -	Bal.	- -	9.0	- -	0.75	- -	- -	2.25	4.5	
MAR-M 509	0.60	21.5	10.0	Bal.	- -	7.0	- -	0.2	- -	0.005	0.5	3.5	
B-1900	0.10	8.0	Bal.	10.0	6.0	0.1[a]	0.1[a]	1.0	6.0	0.015	0.08	4.3	0.015S[a], 0.35Fe[a]
IN-100	0.15	10.0	Bal.	15.0	3.0	- -	- -	4.75	5.5	0.015	0.05	- -	1.0V
Waspaloy	0.07	19.5	Bal.	13.5	4.3	- -	- -	3.0	1.4	0.006	0.09	- -	
Udimet 700	0.10	15.0	Bal.	18.5	5.2	- -	- -	3.5	4.25	0.02	- -	- -	
Alloy 713C	0.12	12.5	Bal.	- -	4.2	- -	2.0	0.8	6.1	0.012	0.10	- -	
MAR-M 200	0.15	9.0	Bal.	10.0	- -	12.5	1.0	2.0	5.0	0.015	0.05	- -	
C 1023 (British)	0.15	15.5	Bal.	9.7	8.4	- -	- -	3.6	4.2	- -	- -	- -	

(a) Maximum

TABLE 9. ADVANCED EXPERIMENTAL SUPERALLOYS

Name	Developer	Nominal Composition, percent													Remarks
		C	Cr	Ni	Co	Mo	W	Cb	Ti	Al	B	Zr	Ta	Other	
AiResist 213	AiResearch	0.18	19	- -	Bal.	- -	4.7	- -	- -	3.5	- -	0.15	6.5	0.1Y	Sheet, combustion chamber liners
AiResist 215	AiResearch	0.35	19	- -	Bal.	- -	4.5	- -	- -	4.3	- -	0.13	7.5	0.17Y	Cast, nozzle guide vanes
B-1910	Pratt & Whitney	0.10	10	Bal	10	3.0	- -	- -	1.0	6.0	0.015	0.10	7.0	- -	Cast, blades and vanes
Haynes Alloy 188	Union Carbide	0.08	22	22	Bal	- -	14	- -	- -	- -	- -	- -	- -	0.08 La, 1.5Fe	Better oxidation resistance than Hastelloy X
IN 738	Intl. Nickel Co.	0.17	16	Bal	8.5	1.75	2.6	0.9	3.4	3.4	0.01	0.10	1.75	Fe,Mn,Si, S, LAP	Cast, sulfidation resistant alloys
IN-792	Intl. Nickel Co.	0.21	12.7	Bal.	9.0	2.0	3.9	- -	4.2	3.2	0.02	0.10	3.9	- -	Good hot corrosion resistance
LDA 204	Lycoming	0.80	25.5	10.5	Bal.	- -	7.5	- -	- -	- -	- -	- -	4.0	- -	Cast, blades + vanes
MAR-M 432	Martin Metals	0.15	15.5	Bal.	20	- -	3.0	2.0	4.3	2.8	0.015	0.05	2.0	- -	Integrally cast turbine wheels
MAR-M 905	Martin Metals	0.05	20	20	Bal	- -	- -	- -	0.5	- -	- -	0.10	7.5	- -	1400 F sheet alloy
MP 35N	Std. Pressed Steel	- -	20	35	35	10	- -	- -	- -	- -	- -	- -	- -	- -	Work-strengthened, fasteners
René 80	General Electric	0.17	14	Bal.	9.5	4.0	4.0	- -	5.0	3.0	0.015	0.03	- -	- -	Blade alloy
René 85	General Electric	0.27	9.3	Bal.	15	3.25	5.35	- -	3.3	5.3	0.015	0.03	- -	- -	Compressor disk alloy
René 95	General Electric	0.15	14	Bal	8.0	3.5	3.5	3.5	2.5	3.5	0.01	0.05	- -	- -	Disk alloy, 900-1200 F range
TAZ 8B	NASA	0.125	6	Bal.	5.0	4.0	4.0	1.5	- -	6.0	0.004	1.0	8	- -	Blades or vanes
TD-NiCr	DuPont	- -	20	Bal.	- -	- -	- -	- -	- -	- -	- -	- -	- -	$2.0ThO_2$	Sheet, bar
TD-NiMo	DuPont	0.5	- -	Bal.	- -	20	- -	- -	- -	- -	- -	0.3	- -	$3.0ThO_2$	Sheet, bar
TRW VI A	TRW	0.13	6	Bal.	7.5	2.0	5.8	0.5	1.0	5.4	0.02	0.13	9	0.5Re,0.43Hf	Blade alloy
Udimet 710	Special Metals	0.07	18	Bal.	15	3.0	1.5	- -	5.0	2.5	0.02	- -	- -	- -	Sulfidation-resistant disk alloy
Unitemp AF2-1DA	Univ. Cyclops	0.35	12	Bal.	10	3.0	6.0	- -	3.0	4.6	0.015	0.10	1.5	- -	Turbine disks or blades

LAP = low as possible

TABLE 10. CASING ALLOYS (Listed in order of increasing heat resistance)

Alloy	Nominal Composition, percent										
	C	Cr	Ni	Co	Mo	Ti	Al	B	V	Fe	Other
EZ 33A	2.7Zn	3.0Re	0.7Zr	- -	- -	- -	- -	- -	- -	- -	Mg. Bal.
HZ 32A	2.1Zn	0.7Zr	3.0Th	- -	- -	- -	- -	- -	- -	- -	Mg. Bal.
HK-31	0.7Zr	3.0Th	- -	- -	- -	- -	- -	- -	- -	- -	Mg. Bal.
2014-T6	4.4Cu	0.8Si	0.8Mn	0.4Mg	- -	- -	Bal.	- -	- -	- -	
2618-T6	- -	0.25Si[a]	1.0	- -	- -	0.07	Bal.	1.3Cu	1.5Mg	1.1	Each 0.05[a], Total 0.15[a]
6061-T6	0.25Cu	0.25	1.0Mg	0.6Si	- -	- -	Bal.	- -	- -	- -	
355-T71	5.0Si	1.3Cu	0.5Mg	- -	- -	- -	Bal.	- -	- -	- -	
356-T6	7.0Si	0.3Mg	- -	- -	- -	- -	Bal.	- -	- -	- -	
Ti-6Al-4V	- -	- -	- -	- -	- -	Bal.	6.0	- -	4.0	- -	
Ti-5Al-2.5Sn	- -	- -	- -	- -	- -	Bal.	5.0	- -	- -	- -	2.5Sn
Ti-6Al-2Sn-4Zr-2Mo	- -	- -	- -	- -	2.0	Bal.	6.0	- -	- -	- -	4Zr, 2Sn
Chromoloy	0.20	1.0	- -	- -	1.0	- -	- -	- -	0.10	Bal.	
AISI 410	0.15[a]	12.5	- -	- -	- -	- -	- -	- -	- -	Bal.	
Greek Ascoloy	0.12	13.0	2.0	- -	- -	- -	- -	- -	- -	Bal.	3.0W
422	0.22	12.0	0.70	- -	1.0	- -	- -	- -	0.25	Bal.	1.0W
Jethete 152 (British)	0.10	12.0	2.5	- -	1.75	- -	- -	- -	0.33	Bal.	
17-4PH	0.06	16.0	4.0	- -	- -	- -	- -	- -	- -	Bal.	3.0Cu
AISI 321	0.08[a]	18.0	10.5	- -	- -	0.60[a]	- -	- -	- -	Bal.	
AISI 347	0.08[a]	18.0	11.0	- -	- -	- -	- -	- -	- -	Bal.	1.0Cb[a]
A-286	0.05	15.0	26.0	- -	1.25	2.15	0.2	0.003	0.30	Bal.	
Incoloy 901	0.05	13.5	42.7	- -	6.2	2.5	0.25	- -	- -	Bal.	
Inconel 718	0.05	19.0	53.0	- -	3.0	0.8	0.6	0.004	- -	19.0	5.2Cb
Inconel X750	0.04	15.0	73.0	- -	- -	2.5	0.8	- -	- -	6.75	0.85Cb
Hastelloy C	0.07	16.0	Bal.	2.5[a]	17.0	- -	- -	- -	- -	5.0	4.0W
Waspaloy	0.07	19.5	Bal.	13.5	4.3	3.0	1.4	0.006	- -	- -	0.09Zr

(a) Maximum

TABLE 11. SHAFT ALLOYS

Alloy	Nominal Composition, percent									
	C	Cr	Ni	Mo	Ti	Al	B	V	Fe	Other
"17-22A"	0.45	1.25	- -	0.50	- -	- -	- -	0.25	Bal.	
B5F5	0.45	1.0	- -	0.55	- -	- -	- -	0.30	Bal.	
AISI 4140	0.40	0.9	- -	0.20	- -	- -	- -	- -	Bal.	
AISI 4340	0.40	0.8	1.8	0.25	- -	- -	- -	- -	Bal.	
H-11	0.35	5.1		1.5	- -	- -	- -	0.40	Bal.	1.0Si
18Ni Maraging Steel	0.03[a]	- -	18.5	4.9	0.65	0.10	- -	- -	Bal.	9.0Co
AM-355	0.15	15.5	4.25	2.75	- -	- -	- -	- -	Bal.	0.10N
A-286	0.05	15.0	26.0	1.25	2.15	0.2	0.003	0.30	Bal.	
Incoloy 901	0.05	13.5	42.7	6.2	2.5	0.25	- -	- -	34.0	0.10Cu
Inconel 718	0.05	19.0	53.0	3.0	0.8	0.6	0.004	- -	19.0	5.2Cb
Waspaloy	0.07	19.5	Bal.	4.3	3.0	1.4	0.006	- -	- -	13.5 Co,0.09Zr

(a) Maximum

TABLE 12. MISCELLANEOUS SHEET ALLOYS

Alloy	Nominal Composition, percent									
	C	Cr	Ni	Mo	Ti	Al	B	V	Fe	Other
Ti-6Al-4V	- -	- -	- -	- -	Bal.	6.0	- -	4.0	- -	
Ti-5Al-2.5Sn	- -	- -	- -	- -	Bal.	5.0	- -	- -	- -	2.5Sn
AISI 410	0.15[(a)]	12.5	- -	- -	- -	- -	- -	- -	Bal.	
AISI 310	0.05	25.0	20.0	- -	- -	- -	- -	- -	Bal.	
AM-350	0.10	16.5	4.25	2.75	- -	- -	- -	- -	Bal.	
N-155, Multimet	0.15	21.0	20.0	3.0	- -	- -	- -	- -	Bal.	0.15N, 20Co 2.5W, 1.0Cb
Inconel 625	0.05	22.0	Bal.	9.0	- -	- -	- -	- -	3.0	3.6Cb
Inconel X-750	0.04	15.0	73.0	- -	2.5	0.8	- -	- -	6.75	0.85Cb
Inconel 718	0.05	19.0	53.0	3.0	0.8	0.6	0.004	- -	19.0	5.2Cb
Hastelloy X	0.10	22.0	Bal.	9.0	- -	- -	- -	- -	18.5	1.5Co, 0.6W
Haynes Alloy No. 188	0.08	22.0	22.0	- -	- -	- -	- -	- -	1.5	Bal. Co, 14.0W, 0.08La
René 41	0.09	19.0	Bal.	10.0	3.1	1.5	0.008	- -	- -	11.0Co
René 63	0.06	14.0	Bal.	6.0	2.5	3.8	0.015	- -	0.5	15.0Co, 3.0W

(a) Maximum

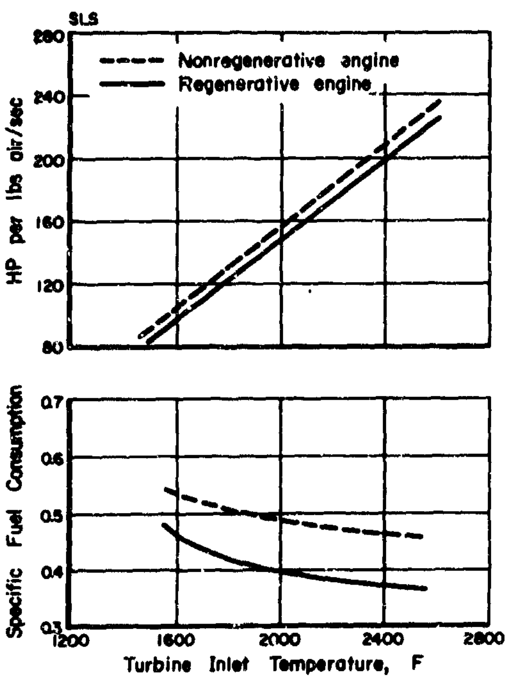

FIGURE 4. INFLUENCE OF TURBINE INLET TEMPERATURE ON ENGINE PERFORMANCE (REFERENCE 2, CURTISS-WRIGHT CORP.)

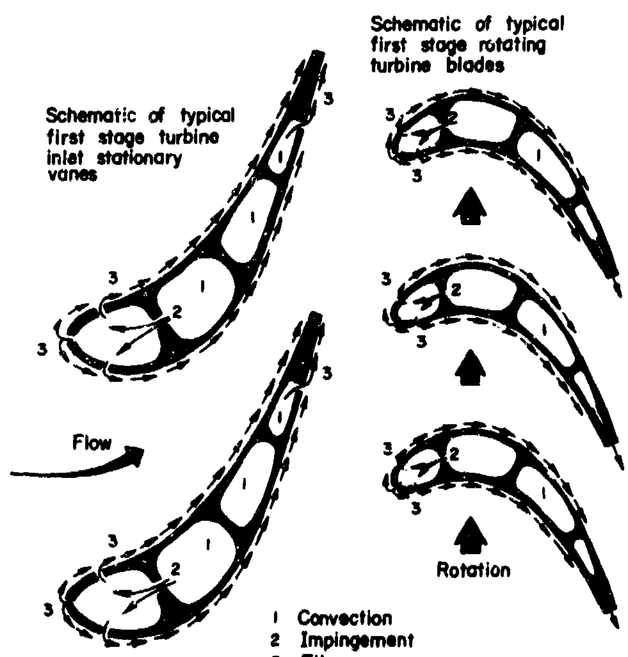

FIGURE 5. SCHEMATIC OF VANE AND BLADE COOLING METHODS (MODIFIED FROM GENERAL ELECTRIC COMPANY INFORMATION)

practical methods of overcoming its deficiencies. Experimental transpiration cooled blades have been tested for only relatively short times, of the order of 100-200 hours; therefore, their resistance to foreign object damage, blocking of pores by dirt, and oxidation damage has not been determined. Figure 6 shows an experimental turbine blade in which the porous mesh has been EB welded to a precision cast spar by Curtiss-Wright Corporation.

Materials trends in turbojet and turbofan engines built by General Electric Company indicate some interesting progressions in materials usage for aluminum/magnesium alloys, titanium alloys, steels, superalloys, and composites, as shown in Table 13.

Superalloys

The selection of new materials for use in aircraft gas-turbine engines is becoming increasingly sophisticated. In addition to long-time strength, ductility, and corrosion resistance considerations, the engine designers are increasingly concerned with such factors as low-cycle fatigue, fracture toughness and crack propagation characteristics, surface and structural stability, fabricability, repairability, and cost. In general, the operating life is now of the order of 15,000 to 30,000 hours in the hot section and up to 50,000 hours in the cold section.

During the next 6-8 years it is expected that the temperature capability of blade and vane materials will be increased by about 100 F over current alloys, with no loss of stability. This development will arise largely from processing inovations rather than modifications in chemistry. Contributing may be directional solidification of eutectics and intermetallics in cast superalloys, and dispersion strengthening of powder metallurgy products by particles or fibers. At the present time, cast alloys appear to have a cost advantage in blades and vanes because the intricate cooling passages can usually be cast more easily than they can be machined.

If cost and production problems can be solved, Pratt & Whitney's directionally solidified or single-crystal turbine blade (Monocrystalloy) process may result in a significant step forward. Many types of elevated temperature failure, including thermal-fatigue cracking and creep-rupture, originate as grain-boundary cracks. Therefore, the absence of grain boundaries normal to the direction of maximum stress in the directionally solidified blades and the absence of all grain boundaries in the single-crystal structure significantly retard the onset of such failures. Pratt & Whitney(1) reports that directionally solidified turbine airfoils have been shown to exhibit up to a ten-fold advantage in rupture and thermal fatigue life over conventional castings of identical composition in certain applications.

Titanium

Although composites will make inroads into the applications of titanium alloys in the fan and front end of the compressor and austenitic alloys will replace some titanium in the hot aft end, there will still be a place for titanium alloys in fan-compressor applications if titanium-alloy development continues. New alloys and new processing methods must improve the properties and lower the

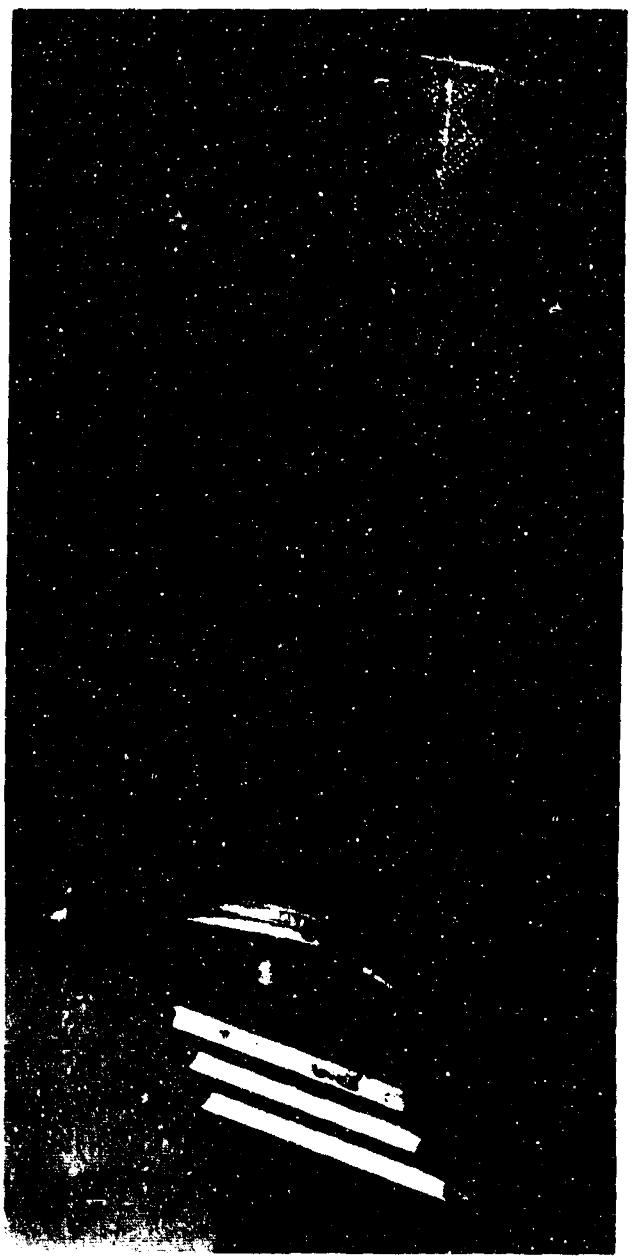

FIGURE 6. EXPERIMENTAL TRANSPIRATION AIR-COOLED TURBINE BLADE
(Courtesy Curtiss-Wright Corporation)

cost of titanium-alloy parts. M. J. Donachie et al of Pratt § Whitney[4] have listed the 1973 and 1978 goals for new titanium alloys (Table 14).

Composites

As shown in Table 13, General Electric Company is predicting that the next generation of jet engines will contain 5 to 10 percent composites. An extensive research and development effort on composites is underway in the U.S., and significant progress is being made. However, fabricability and reliability of composite materials still present problems that are causing U. S. designers to approach the use of composites in stressed parts with caution.

Pratt § Whitney engineers[4] have listed the temperature capability of some current and future composite materials (Table 15) and have plotted the effective strength-density ratios (Figure 7).

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(3) Moskowitz, S. L., and Schober, T. E., "Design and Test of a Small Turbine at 2500 F with Transpiration Cooled Blading", paper presented at the International Automotive Engineering Congress, Detroit, Michigan (January 13-17, 1969).

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(5) Jahnke, L. P., "Fabrication Techniques for Turbine Components", paper presented at the 27th AGARD Propulsion and Energetics Meeting, Paris, France (April 4-7, 1966).

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(8) Simmons, W. F., and Wagner, H. J., "Where You Can Use Today's Superalloys", Metal Progress (June, 1967).

(9) "Rupture Strengths of Selected High-Iron, Nickel-Base, Cobalt-Base, and Refractory Metal Alloys", DMIC Memorandum 236 (May 1, 1968).

(10) "Compilation of Chemical Compositions and Rupture Strengths of Super-Strength Alloys", ASTM Data Series Publication No. DS9d (October, 1967).

TABLE 13. EVOLUTION OF MATERIALS USAGE IN GENERAL ELECTRIC COMPANY AIRCRAFT GAS TURBINE ENGINES

Engine	Design Year	Aircraft	Percent of Material Usage				
			Composites	Al/Mg	Titanium	Steels	Superalloys
J47	1945	F-86, B-47	0	22	0	70	8
J79	1955	F-104, B-58, F-4	0	3	2	85	10
J93	1960	XB-70	0	1	7	24	68
GE4	1965	SST	0	1	12	15	72
TF39	1965	C5A	2	1	32	18	47
Next Generation		——	5-10	1	25	15	50

TABLE 14. PRATT AND WHITNEY GOALS FOR TITANIUM-ALLOY DEVELOPMENT[4]

High-Strength Low-Temperature Alloys	1973	1978	High-Temperature Alloys	1973	1978
R.T. UTS	180 ksi	200 ksi	0.1% Creep/300 hr/ 1000 F	55 ksi	60 ksi
R.T. 0.2% Y.S.	165 ksi	170 ksi	0.1% Creep/300 hr/ 1200 F	30 ksi	35 ksi
R.T. Elong.	15%	15%			
R.T. R.A.	30%	25%	1200 F UTS	100 ksi	120 ksi
R.T., $K_t = 3$, 10^7 Cycle Bending Fatigue Strength, 120 ksi preload	15 ksi	15 ksi	R.T. Elong. after 300 hr/1200 F	8%	6%
R.T., $K_t = 2$, 10^5 cycle fatigue strength	2X Ti6-4	3X Ti6-4	R.T. RA After 300 hr/ 1200 F	15%	12%
R.T. K_{Ic}	60 ksi$\sqrt{in.}$	60 ksi$\sqrt{in.}$			
Creep Strength	Equal Ti6-4	Equal Ti6-4	Safe Stress for No Stress Corrosion After 100 hr/1200F	25 ksi	25 ksi

TABLE 15. TEMPERATURE CAPABILITY EXPECTED OF COMPOSITE MATERIALS (Pratt and Whitney)[4]

Type	Density, lb/in^3	Temperature Range, F	Full Potential By
Carbon Epoxy	0.050	Up to 350	1969
Boron Epoxy	0.075	Up to 350	1969
Borsic Aluminum	0.10	Up to 600	1970
Carbon Polyimide	0.050	Up to 600	1971
Boron Polyimide	0.075	Up to 600	1971
Carbon Polyquinoxaline	0.050	Up to 650	1972
Carbon Polybenzothiazoles	0.050	Up to 750	1973
Borsic Titanium	0.13	Up to 1000	1972
Carbon Nickel	0.19	Up to 1700	1978
Whisker Metal	0.1-0.2	Up to 2500	1978

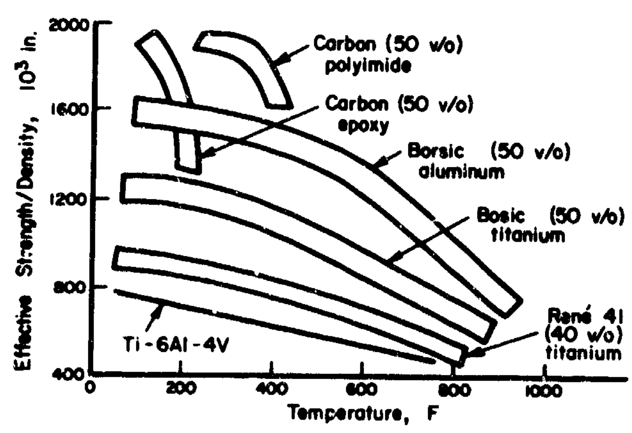

FIGURE 7. EFFECTIVE STRENGTH-DENSITY RATIO OF POTENTIAL FAN-COMPRESSOR MATERIALS VERSUS TEMPERATURE

(Pratt & Whitney Aircraft, Reference 4)

APPENDIX

ENGINE DATA ARRANGED ACCORDING TO MANUFACTURER

APPENDIX. ENGINE DATA ARRANGED ACCORDING TO MANUFACTURER

AiResearch Manufacturing Division, The Garrett Corporation

TABLE A-1. COMPONENTS AND MATERIALS

Component	Material	Component	Material
Fans	Ti-6Al-4V	Shafts	AM355
Compressor			H-11
Stators	410 SS		Alloy 718
Disks	Ti-6Al-4V		AISI 4340
Integral Rotors	Ti-6Al-4V	Gearbox and Housings	MG-EZ33
Combustor	A286		MG-OE22
	Hastelloy X		Al-356
	Inconel X	Gears	AMS 6250
	N-155		AMS 6265
	L-605	Plenum and Drums	AISI 347
Turbine		Low Temperature	AISI 310
Stators	Cast Alloy 713	High Temperature	Hastelloy X
	Cast HS-31		Inconel X-750
	Waspaloy	Bearing Supports	Hastelloy C
	Astroloy		
Integral rotors	Cast Alloy 713		
	IN 100		
	HS-31		

TABLE A-2. ENGINES AND AIRCRAFT APPLICATIONS

Model	Type	Power	Dry Weight, lb.	Applications
TPE331	Turboprop	605/904 ESHP*,TO**	295/355	Aero Turbo Commander, Dinfia AX-2 (Argentina), Carstedt Jetliner, Fairchild-Hiller HeliPorter, Fairchild Turbo Porter, Handly Page C10A, Helio Stallion, Interceptor 400, Mitsubishi MU-2G, Republic Lark (helicopter), S-55T Sikorsky, Skyvan, Swearingen Merlin II B, Swearingen Metro, Volpar Beech 18.
T76	Turboprop	755ESHP, TO	320	OV-10A Bronco
TSE-36-1	Turboshaft	240 SHP, TO	178	Enstrom T-28
TSE 231	Turboshaft	474 SHP	- -	Gates Twin Jet (helicopter)
GTCP 85-291	Turboshaft	190 HP	260	- -
TFE 731	Turbofan	2700/3000 lb thrust	539	Learjet 25
ATF-3	Turbofan	4000/5000 lb thrust	- -	North American Rockwell Series 60 Sabreliner, 330 Hansa Fanjet (West Germany)

* Equivalent shaft horsepower (includes net jet thrust).
** Take off.

Allison Division, General Motors Corporation

TABLE A-3. COMPONENTS, MATERIALS AND PROCESSES

Component	Alloy	Raw Material Form	Fabrication/Assembly Method
		Engine Model 250 and T63-A-5A	
Compressor			
Front Support	AISI 310	Sheet & Rolled Ring	Formed, joined
Case	AISI 410	Sheet & Tubing	Formed, joined
Wheels (1-6)	17-4PH	Precision Castings	Machined
Impeller	17-4PH	Precision Castings	Machined
Vanes (1-6)	AISI 410	Sheet & Strip	Formed, joined
Diffuser Scroll	HZ 32A-T5	Sand Casting	Machined & coated
Diffuser	17-4PH	Precision Casting	Machined
Combustor			
Outer Combustion Case	AISI 347	Sheet & Tubing	Formed, joined
Combustion Liner	AISI 310	Sheet & Tubing	Formed, joined
Turbine fire wall	AISI 310	Sheet & Tubing	Formed, joined
Discharge air tube	AISI 347	Sheet & Tubing	Formed, joined
Gas Producer Turbine			
Turbine Support	PH14-4Mo	Precision Casting	Joined, machined
Wheel (1)	Alloy 713C	Precision Casting	Machined
Wheel (2)	Alloy 713C	Precision Casting	Machined
Nozzle (1)	X-40	Precision Casting	Machined
Nozzle (2)	X-40	Precision Casting	Machined
Tie Bolt	Alloy 901	Forged	Machined
Power Turbine			
Turbine Support	PH14-4Mo	Precision Casting	Joined & machined
Wheel (3)	Alloy 713C	Precision Casting	Machined
Wheel (4)	Alloy 713C	Precision Casting	Machined
Nozzle (3)	X-40	Precision Casting	Machined
Nozzle (4)	X-40	Precision Casting	Machined
Exhaust Collector	AISI 347 + Hastelloy C	Sheet & Casting	Formed, joined
Gear Box			
Gear Box	AZ 92	Sand Casting	Machined & coated
Gears	SAE 9310	Forgings	Machined & carburized
Shafts	AISI 4340 & Nitralloy	Bars & Forgings	Machined & nitrided

TABLE A-3. COMPONENTS, MATERIALS AND PROCESSES (continued)

Component	Alloy	Raw Material Form	Fabrication/Assembly Method
		Turbine Engine TF41-A1 and TF41-A2	
Compressor LP-1P			
Spinner Support	Al 2618-T6	Forging	Machined & coated
Front Casing	Al 2014-T6	Forging	Machined & coated
Split Casing	Al 2618-T6	Forging	Machined & coated
Stator Vane	Al 2618-T6	Forging	Machined & coated
Blade (1-5)	Ti-6Al-4V	Forging	Machined
Stator Vane (3-5)	Jethete	Forging	Machined & coated
Wheel (1-2)	IMI 679	Forging	Machined & coated
Wheel (3-5)	Jethete	Forging	Machined & coated
Compressor HP			
Support	Al C355-T71	Sand Casting	Machined & coated
By Pass Duct	AISI 410	Sheet & Strip	Joined, machined & coated
Vanes (1-11)	H46V	Forging	Machined & coated
Blade (1-5)	Ti-6Al-4V	Forging	Machined
Blade (6-8)	IMI 679	Forging	Machined
Blade (9-11)	H53V	Forging	Machined & coated
Wheel (1-6)	H46V	Forging	Machined & coated
Wheel (7-10)	H53V	Forging	Machined & coated
Wheel (11)	Alloy 901	Forging	Machined
Combustion			
Bypass Duct	AISI 410	Sheet & Strip	Fabricated, joined, machined and coated
Outer Case	Jethete	Sheet & Forging	Fabricated, joined, machined and coated
Inner Case	C263	Forging	Machined
Liner	C263	Sheet & Bar	Joined & machined
Turbine & Exhaust			
Vane (HP 1)	X-40	Precision Cast	Machined
Vane (HP 2)	C1023	Precision Cast	Machined & coated
Vane (LP1-2)	C1023	Precision Cast	Machined
Blade (HP 1)	Nimonic 108	Forging	Machined & coated
Blade (HP 2)	Nimonic 118	Forging	Machined & coated
Blade (LP 1)	Nimonic 105	Forging	Machined
Blade (LP 2)	Nimonic 80	Forging	Machined
Wheel (HP 1-2)	Alloy 901	Forging	Machined
Wheel (LP 1-2)	H53V	Forging	Machined & coated[a]
	Alloy 901	Forging	Machined[b]
Case	Alloy 718	Forging	Machined
Support	Jethete	Forging	Machined & coated
Shaft (LP-HP)	3% Cr,Mo,V	Forging	Machined & coated

TABLE A-3. COMPONENTS, MATERIALS AND PROCESSES (continued)

Component	Alloy	Raw Material Form	Fabrication/Assembly Method
		Turbine Engine Model 501, T56-A-14, T-56-A-15, and T-56-A-16	
Compressor			
Air-Inlet Housing	Al 355-T6	Sand Casting	Machined & coated
Case	AISI 410	Investment Casting	Machined & coated
Stator Vanes (1-14)	AISI 410	Strip-Sheet	Formed, joined & coated
Blades	17-4PH	Forging	Machined
Wheel	9310 Steel	Forging	Machined & coated
Wheel (2 thru 13)	AISI 410	Forging	Machined & coated
Wheel (14)	Nitralloy	Forging	Machined & coated
Shaft	AISI 4340	Forging	Machined & coated
Diffuser			
Assembly	AISI 410	Bar & Forging	Fabricated & coated
Combustion			
Outer Case	Ti-6Al-4V	Sheet	Fabricated & machined
Inner Case	AISI 410	Sheet	Fabricated & machined
Liners & Transition	Hastelloy X	Sheet & Bar	Joined & machined
Shaft (Inner)	AISI 4340	Tubing	Machined & coated
Shaft (outer)	AISI 9310	Tubing	Machined & coated
Turbine			
Case	Hastelloy C	Centrifugal Casting	Machined
Aft Case	AISI 310	Forgings & Sheet	Machined
Vanes (1-2)	Alloy 713	Precision Casting	Machined
Vanes (3-4)	X-40	Precision Casting	Machined
Blades (1-3)	Alloy 713	Precision Casting	Machined & coated
Blade (4)	Waspaloy	Forging	Machined
Wheels (1-4)	Waspaloy	Forging	Machined
Spacers (1-3)	Alloy 901	Forging	Machined
Shaft	AISI 4340	Forging	Machined & coated

(a) For TF41-A1.
(b) For TF41-A2.

TABLE A-4. ENGINES AND AIRCRAFT APPLICATIONS

Model	Type	Power	Dry Weight, lb.	Applications
250	Turboshaft	317 shp	139	Bell Jet Ranger 206A, Hughes 500, Hiller FH 1100
T63-A-5A	Turboshaft	317 shp	139	Hughes OH6A
501	Turboprop	3750 shp (min)	- -	Convair 580
T56-A-14	Turboprop	4900 shp (min)	- -	Navy P3B, Navy P3C
T56-A-15 and T56-A-16	Turboprop	4900 shp (min)	- -	C-130H, HC-130, LC-130
TF41-A1	Turbofan	14,250 lb thrust (min)	- -	LTV A-7D
TF41-A2	Turbofan	14,250 lb thrust (min)	- -	LTV A-7E

Continental Aviation and Engineering Division, Continental Motors Corporation

TABLE A-5. COMPONENTS, MATERIALS, AND PROCESSES

Component	Alloy	Raw Material Form	Fabrication/ Assembly Method
Compressor			
Shafts	17-4PH	Inv. Casting	Machined
	Ti-6Al-4V, Alloy 718	Forging	Machined
Rotors and Blades	17-4PH	Inv. Casting	Machined
	Greek Ascoloy	Forging	Machined
	Aluminum 2014 and 2618	Forging	Machined
	Alloy 718	Forging	Machined
Stators	Aluminum 355	Inv. Casting	Machined
	AISI 347	Bar, Forging Sheet	Formed and Brazed
	AISI 4130	Bar and Sheet	Formed, Brazed and Plated
Housings	Magnesium AZ92A EZ33A and HK31A	Sand Casting	Machined
	Ti-5Al-2.5Sn	Forging and Sheet	Formed and Welded
Combustor			
Outer	AISI 410, N155 Inconel X-750 and 718, L 605	Sheet and Strip	Formed, Welded and Brazed
Inner	AISI 321, N155, Nimonic 75, and René 41	Sheet and Strip	Formed, Welded and Brazed
Housing	AISI 347, Alloy 718	Forging and Sheet	Machined, Formed and Welded
Turbine			
Vanes	HS 21 and 31, L 605, René 41	Investiment Casting, Sheet	Machined Welded
Housing and Shrouds	AISI 321 and 347 N 155, Nimonic 75, René 41	Forging and Sheet	Machined, Formed, Welded
Blades	GMR 235D, Alloy 713C, IN 100	Investment Casting	Machined
Rotors	A286, Alloy 718, Waspaloy	Forging	Machined
Shafts	17-22AS and AV Inconel 718, Waspaloy	Forging	Machined
Other			
Exhaust Duct	AISI 321 and 347, N155, Nimonic 75	Forging and Sheet	Machined, Formed, Welded
Gears	AISI 8617 and 9310	Forging	Machined

TABLE A-6. ENGINES AND AIRCRAFT APPLICATIONS

Model	Type	Power(Thrust-Mil.), lb	Dry Weight, lb	Applications
J69-T-25	Turbojet	1025	364	Cessna T-37B
J69-T-29	Turbojet (Drone)	1700	335	Ryan BQM-34A
J69-T-41A	Turbojet (Drone)	1920	350	Drone Aircraft
J69-T-6	Turbojet (Drone)	1840	360	Ryan BQM-34E
J100-CA100	Turbojet (Drone)	2700	423	Drone Aircraft

General Electric Company

TABLE A-7. COMPONENTS AND MATERIALS

Components	Materials			
	Past Engines	Production Engines	New Engines	Future Engines
Fan				
Blades	- -	Ti-6Al-4V	Ti-8Al-1Mo-1V	Advanced Ti Alloy Hi Modulus Composites
Vanes	- -	Ti-6Al-4V	Ti-8Al-1Mo-1V	Advanced Ti Alloy Hi Modulus Composites
Disks	- -	Ti-6Al-4V	Ti-6Al-6V-2Sn	Advanced Ti Alloy Wound Composite Disk
Compressor				
Blades	AISI 403	Ti-6Al-4V A-286	Ti-6Al-2Sn-4Zr-2Mo Inconel 718	Hi Temp. Ti Alloys René 95
Vanes	AISI 410	Ti-6Al-4V A-286	Ti-6Al-2Sn-4Zr-2Mo Inconel 718	Hi Temp. Ti Alloy René 95
Disks	BSF5	Ti-6Al-4V Inconel 718	Ti-6Al-6V-2Sn René 95	Hi Temp. Ti Alloy Wound Composite Disk Adv. Ni-Base Alloy
Turbine				
Blades	Udimet 500 M-252	René 77 A-286 X-40	René 80	Adv. Ni Blade Alloy
Vanes	René 41	René 41 + 77	TD NiCr	Adv. Ni/Co Alloys
Disks	A-286	Inconel 718	René 95	Adv. Hi Str. Ni Alloy
Structures				
Frame	AZ-92A Chromoloy A-286	Ti-5Al-2.5Sn Inconel 718	17-4PH Inconel 718 René 41	Adv. Ni Sheet Alloy
Casing	HZ-32A Chromoloy A-286	Al-6061-T6 Ti-6Al-4V Inconel 718	Ti-6Al-4V Ti-6Al-2Sn-4Zr-2Mo	René 63
Combustor				
	Hastelloy X Incoloy T (Incoloy 801)	Hastelloy X	Haynes Alloy No. 188	Adv. Ni/Co Alloy

TABLE A-8. ENGINES AND AIRCRAFT APPLICATIONS

Model	Type	Power, lb thrust or HP	Dry Weight, lb.	Applications(a)
J85-4	Turbojet(c)	2950 Max.	404	North American T-2C [2]
J85-5/A	Turbojet(b)	3850 Max.	584	Northrop T-38A [2]
J85-7	Turbojet(c)	2450 Max.	326	McDonnell-Douglas ADM-20
J85-13	Turbojet(b)	4080 Max.	597	Northrop F-5 [2], Fiat G.91Y [2]
J85-15	Turbojet(b)	4300 Max.	615	- -
J85-17/A/B	Turbojet(c)	2850 Max.	400	Cessna A-37 A and B [2], Fairchild Hiller AC-119K and C-123K [2], SAAB-1005-XT[2]
J85-19	Turbojet(c)	3015 Max.	387	Lockheed XV-4B[6]
J85-21	Turbojet(b)	5000 Max.	670	- -
J85/LF1	Lift Fan	14,760 Lift 5,320 Horizontal	2730	NASA XV-5B [2]
J85/LF2	Lift Fan	17,330 Lift 5,820 Horizontal	2420	- -
J79-5C	Turbojet(b)(d)	15,600 Max.	3685	General Dynamics B-58 "Hustler"[4]
J79-7A	Turbojet(b)(d)	15,800 Max.	3575	Lockheed F-104C and D Starfighter
J79-8	Turbojet(b)(c)	17,000 Max.	3672	North American A-5 Vigilante[2], McDonnell F-4A Phantom II[2], McDonnell F4B and RF-4B [2]
J79-10	Turbojet(b)(e)	17,859 Max.	3855	North American RA-5C[2], McDonnell F-4J[2]
J79-11A	Turbojet(b)(d)	15,800 Max.	3560	Lockheed F-104G and J Super Starfighter
J79-15	Turbojet(b)(d)	17,000 Max.	3685	McDonnell F-4C Phantom II and RF-4C [2]
J79-17	Turbojet(b)(d)	17,900 Max.	3835	McDonnell F-4E [2]
J79-19	Turbojet(b)(d)	17,900 Max.	3845	- -
CJ805-3/A	Turbojet	11,200 (T.O.)	3000	Convair 880 [4]
CJ805-3B	Turbojet	11,650 T.O.	2817	Convair 880 M [4]
CJ805-23/B	Turbofan	16,100 T.O.	3766	Convair 990 [4]
CJ610-1/4	Turbojet	2850 T.O.	399/389	CJ 610s (all models) are used on Commodore Jet [2], HFB's Hansa-jet [2], and Learjet [2]. The J85-CAN-40, a modification of CJ610, is used on Canadair CL-41A.
CJ610-5/6	Turbojet	2950 T.O.	402/392	
CJ610-8/9	Turbojet	3100 T.O.	407/417	
CF 700	Turbofan	4200 T.O.	710	Fan Jet Falcon [2]
CF 700-2C	Turbofan	4125 T.O.	725	- -
CF 700-2D	Turbofan	4250 T.O.	735	- -
T58-3	Turboshaft	1325 SHP Max.	309	Agusta Bell 204-B (Italian)
T58-5	Turboshaft	1500 SHP Max.	335	Sikorsky CH-3C/E and HH-3E/F [2]
T58-8B	Turboshaft	1250 SHP	305	Sikorsky HH-52A, Kaman UH-2C [2], Bell X-22A [4]
T58-8E/F	Turboshaft	1350 SHP Mil.	315/305	- -
T58-10	Turboshaft	1285 SHP Max.	350	Sikorsky SH-3A/D [2], Boeing-Vertol CH-46A/D [2]
T58-16	Turboshaft	1481 SHP Max.	440	- -
CT 58-110-1/2	Turboshaft	1350 T.O. SHP	315/335	CT 58s (all models) used on Boeing-Vertol 107 [2], Sikorsky S-61 [2], and Sikorsky S-62
CT 58-140-1/2	Turboshaft	1500 T.O. SHP	340	
CT 64-820-1/-2	Turboshaft or Turboprop	3060 SHP Max.	1130/1145	deHavilland CC-115 and DHC-5 [2], Fiat G.222 [2]
T64-1	Turboshaft	3080 SHP Max.	725	Ling-Temco-Vought XC-142A [4]
T64-3	Turboshaft	3080 SHP Max.	723	Sikorsky HH-53B/C [2]
T64-6	Turboshaft or Turboprop	2850 SHP Max.	723	Sikorsky CH-53A/D [2]
T64-10	Turboprop	2850 ESHP Max.	1167	USAF/NASA C-8A [2], Kawasaki P2J[2], Shin Meiwa PS-1 [4]
T64-12	Turboshaft or Turboprop	3400 SHP Mil.	710	- -
T64-400	Turboshaft or Turboprop	3695 SHP Mil.	710	- -
T64-16/17	Turboshaft or Turboprop	3370 SHP Max.	700/712	Lockheed AH-56A
TF39	High Bypass Turbofan	41,100 Max.	- -	USAF/Lockheed C-5 [4]
CF6-6	High Bypass Turbofan	40,000 Max.	7350	McDonnell-Douglas DC-10 Series 10[4]
CF6-50	High Bypass Turbofan	47,300 Max.	8100	McDonnell-Douglas DC-10 Series 30[4]
GE4/J5P	Turbojet(b)	68,600 Max.	11,303	Boeing 2707-300 [4]
GE12	Turboshaft	1500 SHP	- -	- -

(a) [Bracketed number] is number of engines per aircraft.
(b) Afterburning
(c) Non-afterburning
(d) U.S. Air Force Models
(e) U.S. Navy Models

Lycoming Division, Avco Corporation

TABLE A-9. COMPONENTS, MATERIALS AND PROCESSES

Component	Alloy	Material Form	Fabrication/ Assembly Method
	Turbine Engine Model T53-L-13		
Compressor			
Axial Housing	EZ33A-T5	Sand Casting	Machined
Stator	AISI 321	Rolled Strip	Brazed
Blades	AM350	Forging	Machined
Disks	2014-T6/ Ti-6Al-4V	Forging	Machined
Centrifugal Housing	EZ33A-T5	Sand Casting	Machined
Impeller	Ti-6Al-4V	Forging	Machined
Air Diffuser	AM350/AM355	Sheet, Forging	Formed, Welded Machined, Brazed
Combustor Liner	Hastelloy-X	Sheet	Machined, Formed, Welded
Gas Producer			
1st Stage Nozzle	Alloy 713C	Integral Casting	Machined
1st Stage Turbine Disk	D979	Forging	Machined
1st Stage Turbine Blades	Alloy 713C	Precision Casting	Machined
2nd Stage Nozzle	Alloy 713C	Integral Casting	Machined
2nd Stage Turbine Disk	D979	Forging	Machined
2nd Stage Turbine Blades	Alloy 713C	Precision Casting	Machined
Power Output			
3rd Stage Nozzle Vanes	X40	Precision Casting	Brazed
3rd Stage Turbine Blades	Alloy 713C	Precision Casting	Machined
3rd Stage Turbine Disk	D979	Forging	Machined
4th Stage Nozzle Vanes	X40	Precision Casting	Brazed
4th Stage Turbine Blades	Alloy 713C	Precision Casting	Machined
4th Stage Turbine Disk	17-22AS	Forging	Machined

TABLE A-9. COMPONENTS, MATERIALS AND PROCESSES (continued)

Component	Alloy	Material Form	Fabrication/ Assembly Method
	Turbine Engine Model T55-L-11		
Compressor			
Axial & Centrifugal Housing	HZ32A-T5	Sand Casting	Machined
Stator	AISI 321	Rolled Strip	Brazed
Blades	AM350	Forging	Machined
Disks	AM355/SAE 4340	Forging	Machined
Impeller	Ti-6Al-4V	Forging	Machined
Air Diffuser	AM350/ AM355	Sheet/Forging	Formed, Welded Machined, Brazed
Combustor			
Liner	Hastelloy X	Sheet	Machined, Formed Welded
Gas Producer			
1st Stage Nozzle Vanes	Alloy 713C	Precision Casting	Machined
1st Stage Turbine Blades	Alloy 713C	Precision Casting	Machined
1st Stage Turbine Disk	D979	Forging	Machined
2nd Stage Nozzle Vanes	Alloy 713C	Precision Casting	Machined
2nd Stage Turbine Blades	Alloy 713C	Precision Casting	Machined
2nd Stage Turbine Disk	D979	Forging	Machined
Power Output			
3rd Stage Nozzle Vanes	Hastelloy X	Rolled Airfoil Strip	Brazed
3rd Stage Turbine Blades	Alloy 713C	Precision Casting	Machined
3rd Stage Turbine Disk	D979	Forging	Machined
4th Stage Nozzle Vanes	Hastelloy X	Sheet	Brazed
4th Stage Turbine Blades	Alloy 713C	Precision Casting	Machined
4th Stage Turbine Disk	D979	Forging	Machined

TABLE A-10. ENGINES AND AIRCRAFT APPLICATIONS

Model	Type	Power, SHP	Dry Weight, lb.	Application
T53-L-1A/B	Turboshaft	901 (Mil.)	484	Kaman "Huskie" HH-43B, Boeing-Vertol VTOL, Doak VTOL
T53-L-3	Turboprop	1005 (Max.)	524	Grumman "Mohawk" OV-1
T53-L-9/A	Turboshaft	1100 (Max.)	485	Bell "Iroquois" UH-1D
T53-L-11	Turboshaft	1150 (Max.)	496	Bell "Iroquois" UH-1D, Bell 204 (T5311A, a variant of the T53-L-11)
T53-L-13/A	Turboshaft	1400 (Mil.)	549	Bell AH-1G HueyCobra
T53-L-15	Turboshaft	1203 (Mil.)	605	
T53-L-701	Turboshaft	1450 (Mil.)	685	
CL84 (LTC1K-4A)	Turboshaft	1400 (Max.)	522	Canadair "Dynavert"
LTC 1S-2	Turboshaft	1800 (Mil.)	- -	
T55-L-5	Turboshaft	2200 (Mil.)	570	Boeing-Vertol "Chinook" CH-47A
T55-L-7	Turboshaft	2500 (Max.)	580	Boeing-Vertol "Chinook" CH-47A, Curtiss-Wright X-19 VTOL
T55-L-11	Turboshaft	3750 (Max.)	670	Boeing-Vertol CH-47C
LTC4G-3	Turboprop	2650 (T.O.)	795	North American YAT-28E
LTC 4G-4	Turboprop	2540 (Max.)	795	

TABLE A-11. COMPONENTS, MATERIALS, AND PROCESSES, ADVANCED MILITARY ENGINES

Component	Alloy	Raw Material Form	Fabrication/ Assembly Method
Low Compressor			
Cases	Ti Alloy/AISI 410	Forged/bar/sheet	Machined/welded + machined
Disks	Ti Alloy	Forged	Machined
Blades	Ti Alloy	Forged	Machined
Vanes	Ti Alloy/AISI 410	Forged/strip	Machined/roll formed
High Compressor			
Cases	Inconel X-750	Forged/bar/sheet	Machined/welded + machined
Disks	Incoloy 901	Forged	Machined
Blades	Incoloy 901	Forged	Machined
Vanes	Inconel X-750	Forged/strip	Machined/roll formed
Diffuser			
Case	Alloy 718	Forged/cast	Machined/welded + machined
Burner			
Cases	Alloy 718	Sheet	Rolled/welded
Liners	Hastelloy X/ TD Nickel	Sheet	Formed/welded/diffusion bonding
Dome	TD Nickel	Sheet	Formed/welded
Nozzles	Haynes Stellite 31	Cast	Machined
Turbine			
Cases	Waspaloy/ Alloy 718	Forged	Machined
Disks	Waspaloy	Forged	Machined
Blades	B-1900/ Alloy 713	Cast	Ground fir tree
Vanes	MAR-M-302/ B-1900	Cast	Machined
Turbine Exhaust			
Cases	Alloy 718/ Ti Alloy	Sheet	Welded
Accessory			
Shafts	AISI 8740	Forged	Machined
Gears	AISI 9310	Forged	Machined
Housing	Magnesium	Cast	Machined
Main Shafts			
Low	17-22A	Forged	Machined
High	Incoloy 901	Forged	Machined

TABLE A-12. ENGINES AND AIRCRAFT APPLICATIONS

Model	Type	Power	Dry Weight, lb.	Applications
J52-P-8A	Turbojet	9300 Thrust Mil.	2118	Douglas A-4F, Douglas TA-4F, Grumman A-6A
J60-P-6	Turbojet	3000 Thrust Mil.	495	North American T-2B
TF30-P-8	Turbofan	12,200 Thrust Mil.	2526	LTV A-7B
TF30	Turbofan*	20,000 Thrust Class		Grumman F-14A, General Dynamics/Grumman F-111
TF33-P-7	Turbofan	21,000 T.O. Thrust	4675	Lockheed C-141
T73-P-700	Turboshaft	4800 T.O. SHP	981	Sikorsky CH-54B Flying Crane
JT3D-3B	Turbofan	18,000 T.O. Thrust	4260	Boeing 707-120B, 320 B & C, 720 B Douglas DC-8-50, 50F, 61, 61F, 62F, 63 VC-137C (Presidential plane)
JT3D-7	Turbofan	19,000 T.O. Thrust	4260	Boeing 707-120B, 320B + C,720B Douglas; DC-8-62, 62F, 63, 63F
JT8D-7	Turbofan	14,000 T.O. Thrust	3156	Boeing 727, 737 Douglas DC-9 Caravelle 10B, 10R, 11R
JT8D-9	Turbofan	14,500 T.O. Thrust	3218	Boeing 727, 737 Douglas DC-9 Caravelle 10B, 10R, 11R
JT8D-11	Turbofan	15,000 T.O. Thrust	3310	Boeing 727, 737 Douglas DC-9 Caravelle 10B, 10R, 11R
JT9D-7	Turbofan	45,500 T.O. Thrust	8770	Boeing 747 McDonnell Douglas DC-10 Series 20
PT6A-20	Turboprop	550 T.O. SHP	275	Pilatus P-3 Military Trainer, and 16 light commercial aircraft

* with afterburner

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This memorandum discusses the applications of heat-resistant metallic materials in aircraft gas turbine engines. Brief background information on the engines of each of the manufacturers is followed by a detailed discussion of the materials used in various components of the engines. Some current trends in turbine-engine materials applications are pointed out. An extensive appendix arranged according to manufacturer, lists materials used in recent and current engines and presents some brief data on size, weight, and application of each of the engines.

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